# HIGH CURRENT AND HIGH POWER FAST KICKER SYSTEM CONCEPTUAL DESIGN AND TECHNOLOGY OVERVIEW FOR DEEME EXPERIMENT[*]

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## Abstract

A US-Japan collaboration for the high energy physics experiment DeeMe requires a multi GVA high deflection strength fast kicker system. A set of high current, high voltage and high power generators are going to drive a series of kicker magnets to deflect passing beam. Brookhaven researchers have been invited to conduct a conceptual design study for this challenging project. The basic option consists of a set of identical modulators, low impedance transmission lines, and large aperture high inductance kicker magnets. Each modulator shall be capable of driving the kicker magnet with an 8kA to 10kA pulsed current. A desired fast pulse fall time of 300 to 400 ns is the most challenging part of the design because of the high inductance magnetic load. The after pulse floor ripple tolerance is 5% or best achievable. Pulse repetition rate is 25Hz continuously.

We have evaluated a wide range of pulsed power technology options and concluded that the requirement is beyond the state of the art for fast kicker technology. However, a near perfect solution is possible. We proposed several options in the conceptual design for the best achievable technical solution.

In this paper, we present the technology overview, design comparisons, and the areas requiring advanced research and development effort.

## I. INTRODUCTION

DeeMe is a proposed high energy physics experiment collaborated by U.S. and Japanese scientists. The experiment is going to be located in Japan Proton Accelerator Research Center (J-PARC) H muon beam line (H-line). To divert beam from the main detector, the experiment requires a fast secondary beam line kicker to kick away the charged particles in the prompt-burst as cleanly as possible.

Kickers are a class of pulsed power system used in particle accelerators around the world. Their primary function is to provide electromagnetic force that changes the trajectory of charged particles in a fast, repeatable, and precision manner.

A typical kicker system consists of a set of pulse generators, beam deflectors, instrumentation and controls, and a set of pulse transmission cables if generators were located outside beam enclosure such as accelerator tunnels.

DeeMe physicists specified basic requirements of the fast kicker including main parameters and constrains. The experiment would like to have pulse generators outside the beam line enclosure except cable termination and load compensation boxes; and magnet system should be stand alone and fit into the H-line space.

Additional requirements included radiation hardness design, electrical grounding and noise shielding, magnetic interference minimization between adjacent beam lines and adjacent etc.

### A. H-line Description

The H-line beam line is in J-PARC's Materials and Life Science Facility (MLF); it has movable shielding blocks to allow access when beam is off.

The expected ionized radiation level at H-line kicker location is about 1 Rem per hour during beam operation.

Because of the limited space, 1.6 meter line width, at H-line experimental area and the radioactive environment,

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the power modulators must be located outside the beam line enclosure except high voltage pulse cable terminations and load compensation network boxes, pulsed current measurement devices, and their enclosures.

### B. Main Parameters

We list Main Parameter Specifications of the DeeMe Fast Kicker System in Table 1 as given by Japan Institute of High Energy Physics (KEK).

**Table 1.** Specification of DeeMe Fast Kicker System Main Parameters

| | |
|---|---|
| Total Deflection Strength | > 0.0616 T-M |
| Flatness of the "flat-top" | Not required |
| Window Gap | 320 mm Preferred |
| Window Width | 320 mm |
| Total Effective Length | 2500 mm |
| Number of Kicker Sections | 4 Suggested |
| Rise Time | Any |
| Fall Time | ~300 ns; as fast as reasonably achievable |
| Pulse Length | > 1 $\mu$s |
| Repetition Rate | 25Hz |
| Momentum of the Beam | 105 MeV/c |
| Charge of the Beam | Negative |
| Type of the Beam Particle | Mostly electrons |
| Kick Angle | 174 mrad |
| Kick Direction | Either horizontal or vertical (Do not care) |

To reach a better then 90% transmission rate, a desirable floor ripple level after the main pulse shall be within ± 5%.

## II. PARAMETER EVALUATION

We started our conceptual design by evaluating requirement and main parameters.

There are several types of kicker deflectors, such as parallel plate strip-lines, parallel wires, lumped magnet, semi-lumped magnet, and traveling wave magnet structures. The common choice in high deflection kicker design is to use magnetic deflector for higher deflection efficiency within limited longitudinal space.

The real estate space at beam line is precious. Therefore, the design of beam line components must be efficient in space utilization. The preliminary H-line design layout slotted a 2.5 meter length for kicker chamber. However vacuum chamber flanges, and internal spaces reserved between adjacent magnet sections high

voltage conductors and to the chamber flanges will take away some mechanical length, the resulting maximum useful length for kicker magnet is estimated at 2.2 meters.

To reach 0.0616T-M deflection strength with 2.2 meter magnetic kicker, the required magnetic field strength is 0.028 Tesla. The specified magnet window gap and window width are 0.32 meters. Therefore, the required kicker current is about 7130 amperes assuming a 2.2 meter effective kicker length.

With a large magnet gap, the large leakage field and magnetic coupling between adjacent magnet sections, and magnetic field leakage to adjacent beam line components and systems are of serious concern. To achieve low interference requirement, we used special geometry and coil design in our study. However, to accommodate this geometry the kicker current has to be increased to 8064 amperes. The description and simulations are presented in the later chapter.

Considering the high current amplitude, a low impedance design is preferred in order to keep voltage within a reasonable range. For example, a typical design of a pulse generator with 50 ohm impedance pulse-forming-network, 10kA output current, driving a magnet with matched impedance termination resistor, would require a high voltage design of 1 Mega-volts. In practice, most kicker designs are limited under 50 kV, a few are extended to 80kV or 100kV. The voltage limit is due to device and material sustainability and availability, physical dimension of the device and equipment, and operation reliability.

The most challenging part of the design is to meet the fast electromagnetic field fall time requirement of 300 nano-seconds through a large inductive load. In most situations, a fast pulse fall time is much harder to achieve than a fast rise time. Contributing factors include the switch characteristics, transmission cable high frequency attenuations, network behaviors, and etc.

The DeeMe beam line kicker is a multi GVA high peak power and high repetition rate fast kicker. The pulse generator and pulse transmission, kicker deflector, and control centre are the main parts of the system.

Over last few decades, the control technology has progressed and matured. Most accelerator kicker systems are designed with standardized industry equipments such as using programmable logic controllers for command control and status monitoring, using multi-channel pulse delay generators for timing and system synchronization, using digital oscilloscope and digitizer for waveform monitoring, and etc.

The pulse generator technology for application in light source and electron accelerator is moving rapidly toward commercialization. It remains to be a challenging technical area in high power kicker design for high energy hadron accelerators. Almost all high power kickers are designed, developed, and constructed in accelerator laboratories. However, the technology transfer from laboratory to industry is ongoing in several countries.

The ideal option would be a perfect impedance matched transmission line system with an ideal switch that can open and close on demand. Although the technology is moving toward that direction, it still has long way to go. The industry responses to our preliminary solicitation of proposals also validated this fact.

To find a technical solution, we evaluated many design options including:

- PFN/PFL modulator topology of various impedances
- Impedance matching networks
- Matched and mismatched load impedance effects
- Blumlein pulse generator topology
- Marx Generator topology
- Capacitor discharge with opening switch topology
- The end of line tail-bite topology
- Load side tail-bite topology
- Lumped magnet
- Semi-lumped magnet
- Travelling wave magnet
- …

We also considered shock line method and nonlinear transmission line method.

Comparing the technical performance, the potential cost, and the project schedule of various options, we believe a modular approach with four identical subsystems is reasonable. Each will consist of a pulse generator with a low impedance PFN/PFL topology, delivering pulse through a set of pulse transmission lines to a compensated lumped magnet load.

# III. CONCEPTUAL DESIGN OF ILLUSTRATIVE MAGNET SYSTEM

## A. Illustrated Magnet Chamber Layout

The fast kicker magnet will be designed as a lumped mass, rectangular window frame magnet. Four magnet modules will form a single train and installed in a single chamber with acceptable distance between each other. The vacuum Chamber will be a rectangular shape with round corners to save room in the two sides.

The window frame core of the magnet will use CMD 5005 Ni-Zn type ferrite blocks. This type of ferrite has high frequency response, very low eddy current loss and is high vacuum compatible. The coil will be made of a single-turn copper sheet conductor. Due to large aperture, the loop of the conductor from upper sheet to lower sheet will sit in the inner edge of the two core ends. This arrangement will reduce coupling effect between the adjacent magnets. In the middle of the ferrite back leg a copper strip may needed to carry beam image current for reducing beam impedance. The other purpose of the strips

is to damper beam induced pulsed fields in the ferrite core.

High voltage current will be fed from top of each magnet. Due to higher voltage and current, a custom made feed-through may be needed to fit in the limited space. A conceptual figure of the magnet with chamber is attached for reference.
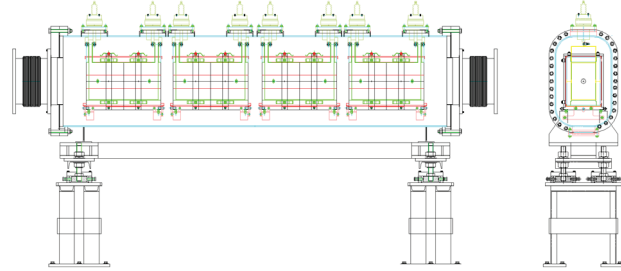


**Figure 1.** The illustrated magnet chamber layout

In this drawing, we showed two feed-through per magnet section to demonstrate there is sufficient space to accommodate different load compensation circuit and layout designs. The actual mechanical design of magnet and feed-through will depend on the chosen electrical circuit design and R&D results.

## B. Magnetic Structure

To reduce magnetic field coupling between magnet sections and to minimize leakage field we propose a magnet structure using internal coil return inside magnet aperture.

We considered a wide width option and a narrow width option. Assuming four kicker sections and a total magnetic length of 2.2 meter, the inductance of each section of the wide width design and narrow width design are 0.815 micro Henry and 0.791 micro Henry, respectively.

The proposed wide width magnet structure is shown in Figure 2.
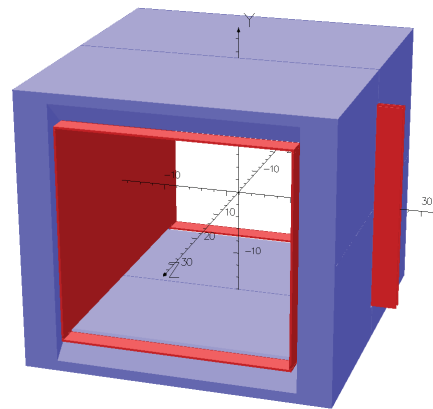


**Figure 2.** Illustrated magnet structure

In this design, the core length is 50 cm; the core material is CMD5005; its edge chamfer size is 4 cm x 3.5

cm. The ferrite window gap is 0.32 meter, and its width is 0.36 meter for wide width option and 0.327 meter for narrow width option. Its central hole cut for current leads are 2 cm m by 32 cm.

This structure design has higher magnet inductance than conventional structure, and also it requires higher current. However, we believe it could offer better performance.

## IV.   CONCEPTUAL DEISGN OF PULSE GENRATOR SYSTEMS

The kicker system will include multiple sets of identical subsystem consisting of a pulse generator, a set of pulse transmission cables, kicker magnet and termination box, auxiliary power system, and subsystem control and instrumentation; and a central communication and control system. The modulators and the auxiliaries will be located in equipment area, the magnet chamber will be located in H-line, high voltage pulse cables will connect modulators and magnets.

Our evaluation reached a similar conclusion with KEK colleagues that a low impedance PFL or PFN pulse generator with mismatched load termination would be the preferred technical solution. As requested by DeeMe experimenters, we offered three designs for consideration.

### A.  Option 1

In this option, we proposed a reconfigurable and upgradable pulse generator and magnet system. The selected topology of pulse generator is a pulse-forming-network (PFN) based circuit implementable by a set of pulsed cables (pulse-forming-line, PFL) or discrete inductors and capacitors. We propose a lumped magnet structure, as a baseline design, with impedance matching network capacitor and parallel resistor without series pulse termination resistor. This would allow current amplitude doubling at the load magnet. The pulse modulators' PFN/PFL and transmission cables shall be capable to with stand a hi-pot potential of 100kV to allow reconfiguration. The initial charging power supply shall be rated at 60kV or higher.

The main advantage of using long transmission cable is to delay the pulse reflection after the main pulse and provide a cleaner time window for experiment. For transmission cable delay of 3µs, each cable length will be about 2,000 feet, and 10 cables in parallel to achieve 5 ohm impedance. This will require 20,000 feet of transmission cable per unit.

The cable length of PFL and transmission will be 26,500 feet cable per unit;  the total cable length for a system of four magnet sections and four PFL modulators will be 106,000 feet. This large quantity of cable will occupy a large cable yard and cable tray system for storage and transmission.

This option is the most expensive one. In addition, there are technical issues such as cable attenuation, switch on

duration, heat dissipation, construction, installation, and storage space, etc. involved.

### B.  Option 2

The high voltage modulator using pulse-forming-network has the advantage of compactness. It offers comparable performance, lower cost, and some degree of impedance and waveform adjustability.

In this design we propose to use a transmission cable delay of 300ns, about 180 feet to 200 feet each length, to reduce cable cost and simplify the installation task.

A 6.25 ohm, 60kV system is shown in Figure 3 and its simulated PFN voltage and magnet current waveform is shown in Figure 4.

In comparison a 5 ohm, 50kV kicker circuit is also considered and simulated. This alternative would improve the system reliability with lower voltage in exchange of slower pulse fall time.

### C.  Option 3

DeeMe has offered an option of 3.0 meter long kicker chamber for design and cost comparison. We presented a design with a 2.5 meter total magnetic length, six magnet sections, driving by six PFN modulators, and transmitted through a set of 180 feet long pulse cables. The required magnetic field is 0.0246 Tesla, and the magnet current is 6274.52 Ampere. The modified parameters are listed in Table 2.

**Table 2.** Option 3 Main Parameters

| Deflection strength | 0.0616 | T-M |
|---|---|---|
| Total effective magnet length | 2.5 | M |
| Magnetic field strength | 0.0246 | Tesla |
| Magnet window height | 0.32 | M |
| Number of turns | 1 | |
| Magnet current | 6275 | A |
| Number of sections | 6 | section |
| Effective magnetic length per section | 0.417 | M |
| Magnet window width | 0.32 | M |
| Magnet inductance per section | 0.524 | µH |
| Stray inductance per section | 0.600 | µH |
| Total inductance per section | 1.124 | µH |
| Pulsed field fall time | 300 | ns |

The principle circuit of option #3 and its simulation result are shown in Figure 5 and Figure 6.This option offers a near perfect solution to the DeeMe specification.

### D.  Comparison

Since the proposed system in Option 1 is reconfigurable, the experimenter may change the system impedance according to their experimental need for different experiment. However, this Option is difficult to implement due to large cable quantities.

The proposed 6.25 ohm PFN system in Option #2 is achievable, but operating at the limit of pulsed cable and feed-though. It would offer an acceptable pulse fall time

around 400 ns and the floor ripple would be within the tolerance. It would produce the required field strength to sweep out the prompt bursts and remain on low noise state for 4 μs period. It would be capable to operate at 25 Hz pulse repetition rate. A 70kV high voltage power supply is available on the market to allow some operation margin. If the better reliability is desired, then the alternative 5 ohm system shall be used. It has a fall time of 560 ns.

Another way to reduce the field fall time and voltage is to extend the kicker chamber length to 3 meters and use 6 magnet sections and 6 modulators, such as the one proposed in Option 3. The performance would be better due to lower magnet inductance per section.

All major components and materials are available on the market.

# V. SUGGESTED RESEARCH AND DEVELOPMENT

Since the required performance is beyond the state-of-arts of the kicker technology, we suggest an upgrade path to achieve better performance. Several key areas require new research and development efforts.

The research and development in high voltage, high current, high speed solid-state switches are necessary due to fast shrinking, or disappearing, thyratron market. This is a serious threat to the experiment. A few manufactures have started the solid state switch development and progress in the field is remarkable. We have received the vendor response to collaborate on solid state switch R&D.

The large inductance of lumped magnet limits the fall time speed of field waveforms. Low impedance travelling wave magnet capable of handling 10kA and 100kV is well beyond the state-of-arts. A semi-lumped magnet might be a viable solution.

The inductance and the physical size of the high voltage vacuum feed-through is a limiting factor in the design. An effort to lower the inductance of feed-through and to reduce its size would be necessary for semi-lumped magnet development and would benefit the performance of lumped magnet design.

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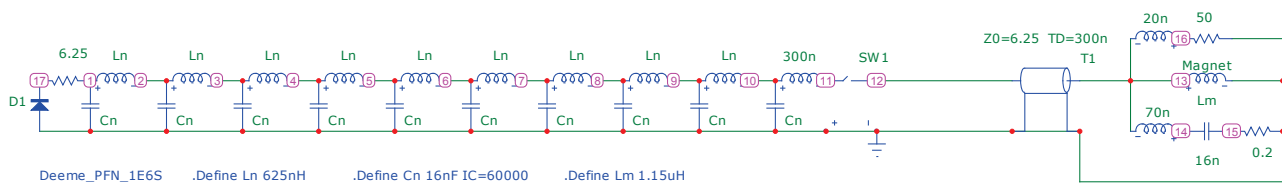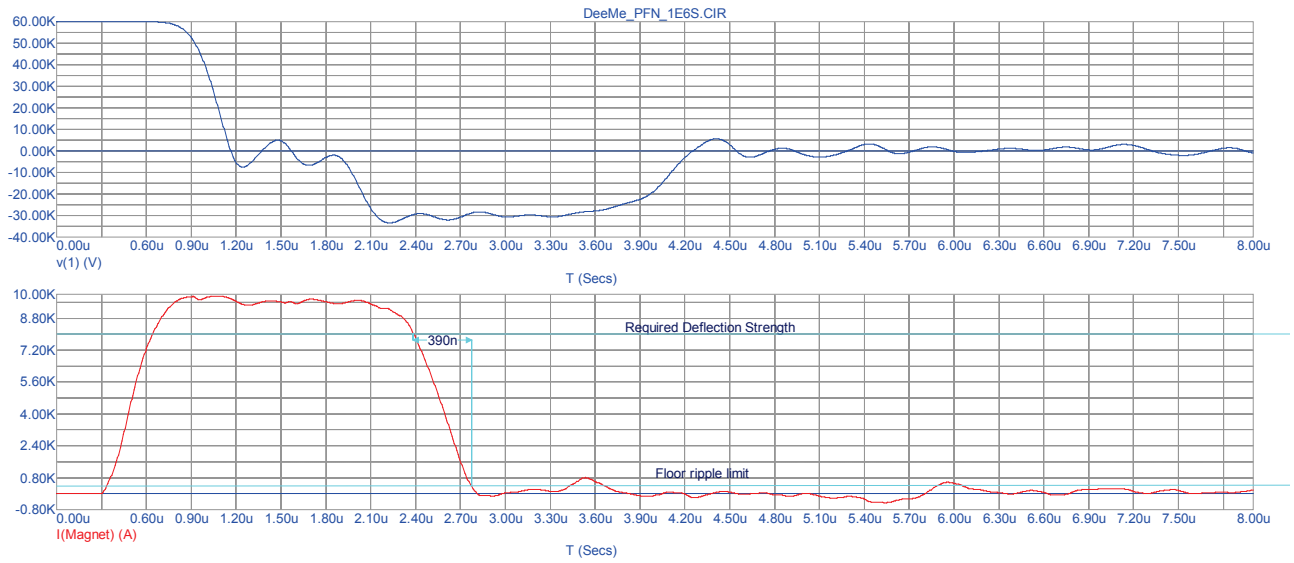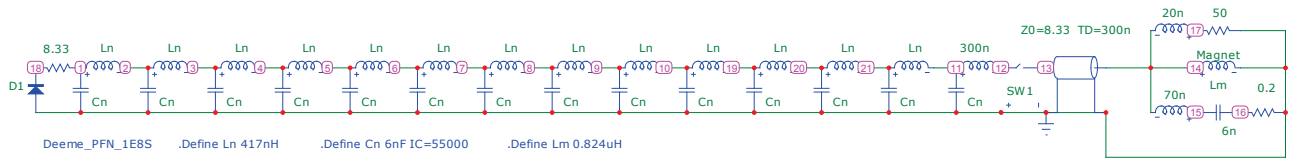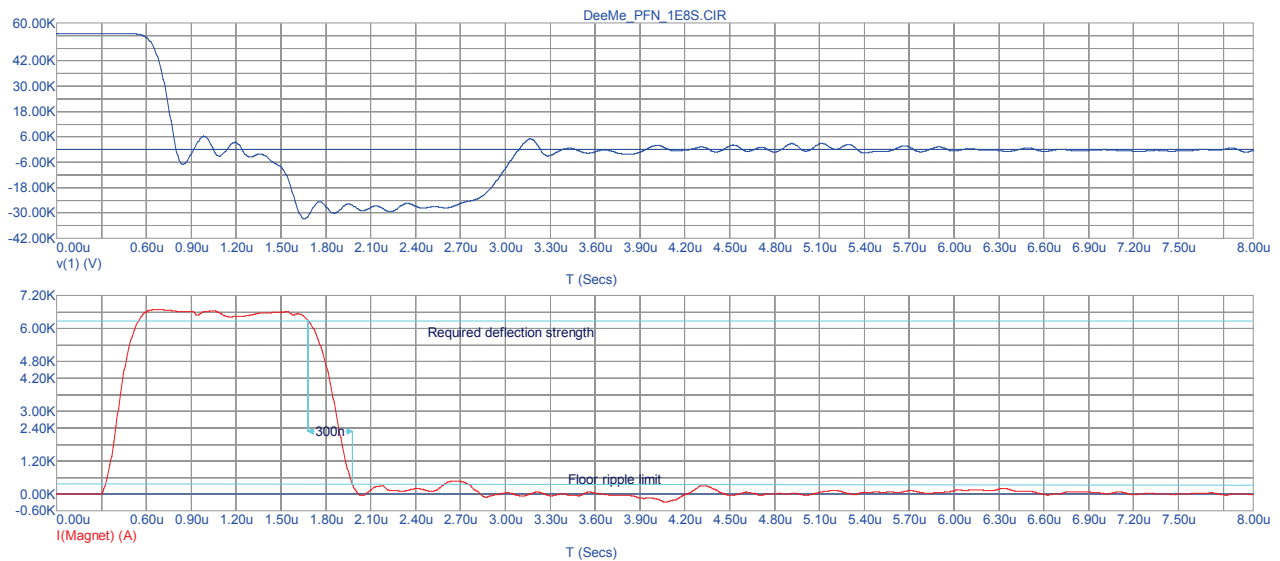
**Figure 3.** Option 2, a 6.25 ohm impedance kicker system

**Figure 4.** The upper trace is the PFN voltage waveform, and the lower trace is the magnet current waveform of Option 2.



**Figure 5.** Option 3, an 8.33 ohm impedance kicker system



**Figure 6.** The upper trace is the PFN voltage waveform, and the lower trace is the magnet current waveform of Option 3.